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Solar Cells for Lunar Application

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Executive Summary

In this work a preliminary study of the vacuum evaporation of silicon extracted from the lunar regolith has been undertaken. An electron gun vacuum evaporation system has been adapted for this purpose. Following the calibration of the system using ultra high purity silicon deposited on Al coated glass substrates, thin films of lunar Si were evaporated on a variety of crystalline substrates as well as on glass and lightweight 1 mil (25 μm) Al foil. Extremely smooth and featureless films with essentially semiconducting properties were obtained. Optical absorption analysis sets the bandgap (about 1.1 eV) and the refractive index (n=3.5) of the deposited thin films close to that of crystalline silicon. Secondary ion mass spectroscopy and energy dispersive spectroscopy analysis indicated that these films are essentially comparable to high purity silicon and that the evaporation process resulted in a substantial reduction of impurity levels. All layers exhibited a p-type conductivity suggesting the presence of a p-type dopant in the fabricated layers. While the purity of the "lunar waste material" is below that of the "microelectronic-grade silicon", the vacuum evaporated material properties seems to be adequate for the fabrication of average performance Si-based devices such as thin film solar cells. Taking into account solar cell thickness requirements (>10 microns) and the small quantities of lunar material available for this study, solar cell fabrication was not possible. However, the high quality of the optical and electronic properties of evaporated thin films was found to be similar to those obtained using ultra-high purity silicon suggest that thin film solar cell production on the lunar surface with *in situ* resource utilization may be a viable approach for electric power generation on the moon.

INTRODUCTION AND BACKGROUND

The nation's space exploration initiative, and specifically its lunar component, has major requirements for technology development of critical systems, one of which is electric power. The availability of significant electric power at the surface of the moon will be a principal driver defining the complexity of a lunar base. 100 kW is called for in the first phase of the lunar base (Cohen 1989), however, this will grow to over 1 MW during the utilization phase of the base. Proposals to generate power on the moon include both nuclear and solar (photovoltaic) systems. The main drawback to all of the approaches to date is that all of the mass for the power system must be transported from the earth to the moon. For the lunar base this could amount to over 40 metric tons to the moon for the utilization phase. A more efficient (and possibly synergistic) approach is to attempt to utilize the existing lunar resources to implement power generation systems. Synergy lies in the fact that there is an ultra-high vacuum environment on the surface of the moon where most of the materials required to fabricate thin film solar cells are already available. The vacuum environment is directly applicable to vacuum epitaxial growth (Frass 1990) and to the development of thin film solar cells (Werner 1994, Wenham 1996). There have already been lunar regolith processing techniques proposed (Sullivan 1991, Bhogeswara Rao 1979) that would have elemental by-products that could be specifically used to generate thin film solar cells.

Lunar resource utilization has focused principally on the extraction of oxygen from the lunar regolith (Gibson 1990). A number of schemes have been proposed for oxygen extraction from Ilmenite and Anorthite. These schemes have as their by-products (or more directly as their "waste products") materials such as Si and Al, which are specifically needed for the fabrication of silicon solar cells. Pressures on the surface of the moon are generally in the 10^{-10} Torr range or better, thus representing a near-ideal environment for direct vacuum deposition of thin films using the 'waste' Si present on the moon. The proof-of-concept of lunar vacuum evaporation of waste-Si thin film on low cost lightweight substrates, such as Al-foil, promises to have a major impact on the lunar exploration initiative and power generation using resources available on the surface of the moon

In this work a preliminary study of the vacuum evaporation of silicon extracted from lunar regolith (Keller, 1989) has been undertaken using a conventional electron gun evaporation technique. Thin films were evaporated on variety of crystalline substrates, glass, and lightweight 1 mil Al-foil. The structural and optical properties of these films are investigated. Different tasks carried out under this contract included

1 - Adaptation of a vacuum system for the evaporation of lunar-Si
2 - Testing of different surface preparation techniques and testing possibilities of evaporating onto ultra-lightweight substrates
3 - Optimization of low temperature Si growth on various substrates including Al-foil
4 - Assessment of a processing technology compatible with thin-Si/1 mil Al cell processing
5 - Evaporation of lunar-Si thin films on various substrates
6 - Study of structural and opto-electronic properties of lunar-Si thin films
7 - Technology viability evaluation and identification of future improvements.

The study of lunar-Si thin films properties included the following characterization techniques

- Morphology: using micro-mechanical profilometry, optical microscopy and electron microscopy
- Crystalline properties: X-ray diffraction
- Optical properties: Optical transmission/absorption (bandgap), interferometry (refractive index)
- Electrical characterization: current-voltage, film resistivity, residual carrier type, carrier mobilities
- Impurity analysis of films: Secondary Ion Mass Spectroscopy, Energy Dispersive Spectroscopy

ADAPTATION OF A VACUUM SYSTEM FOR THE EVAPORATION OF LUNAR-SILICON

Because of the high temperatures required for Si evaporation, and in order to avoid contamination from the container (crucible), an electron beam evaporator was used. The evaporator has been designed to allow the evaporation of eight different species with the possibility of co-evaporating two elements/products simultaneously (e.g. Si and a dopant material).

A Photograph of the experimental evaporation set up is provided in Fig 1.

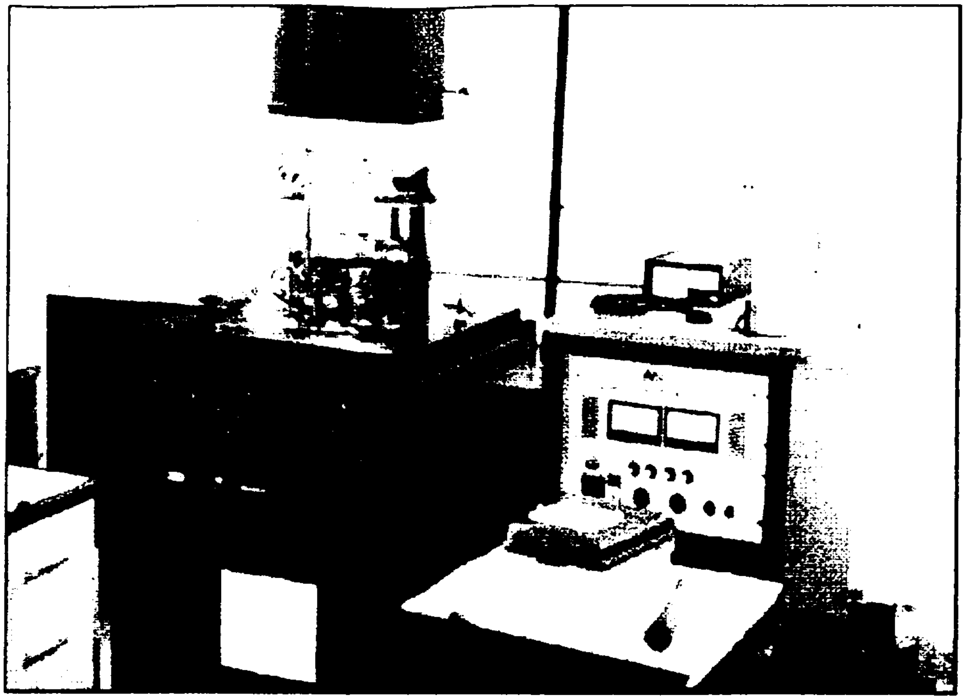


FIGURE 1: Photograph of Electron -Beam Evaporator Adapted for Lunar-Si Thin Films

Although e-beam evaporators with vacuum levels comparable to those encountered on the surface of the moon (10^{-10} Torr) can be realized on earth. Due to budgetary constraint in this preliminary phase, the system was rebuilt to operate in the 10^{-7} Torr vacuum range. Most recently, a limitation in evaporating dopant materials such as As was encountered. Nevertheless, the system proved to be workable with growth rates exceeding 5-10 microns per hour.

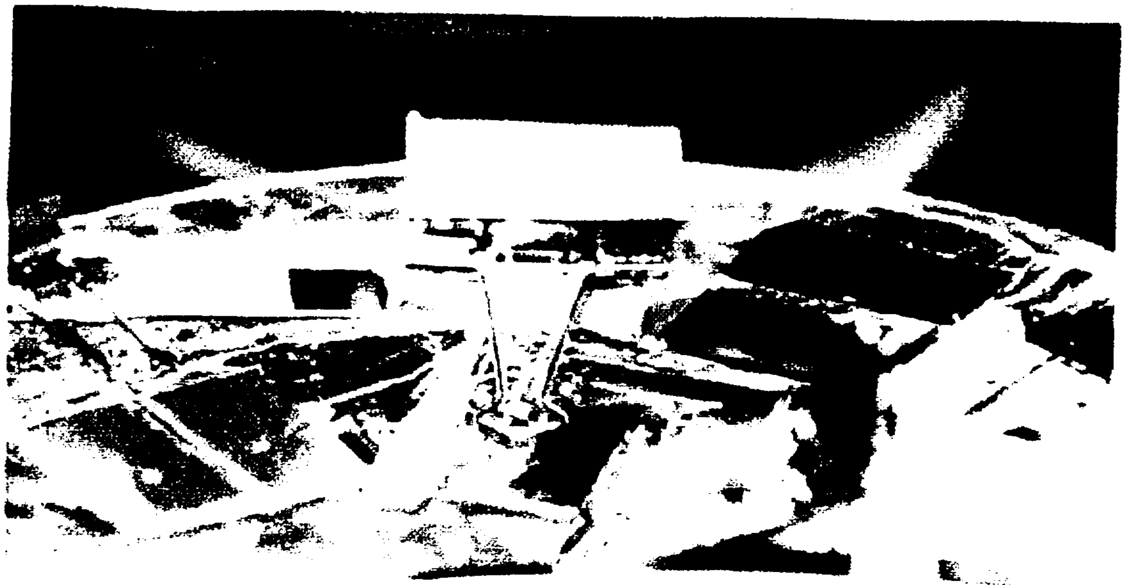


Figure 2 (a): Photograph of Substrates Mounted in the Evaporator

Figure 2 (a) Photograph of the Electron Gun/Evaporation Crucibles

SUBSTRATE SURFACE PREPARATION TECHNIQUES

Prior to and during the development and adaptation of the evaporation system, we developed surface preparation techniques to allow for use of projected substrates such as thin Al foil. In order to stay compatible with the potential mission scenario, preparation included a chemical cleaning of the sample surface followed by a period of about 3 days storage in a clean room environment to imitate the scenario of a pre-launch (one may assume that following preparation substrate foil can be kept in an average vacuum canister during launch until its arrival on the moon).

Comparison of morphology and adherence of thin Si-films obtained through conventional 7 nines purity Si was used to qualify the process.

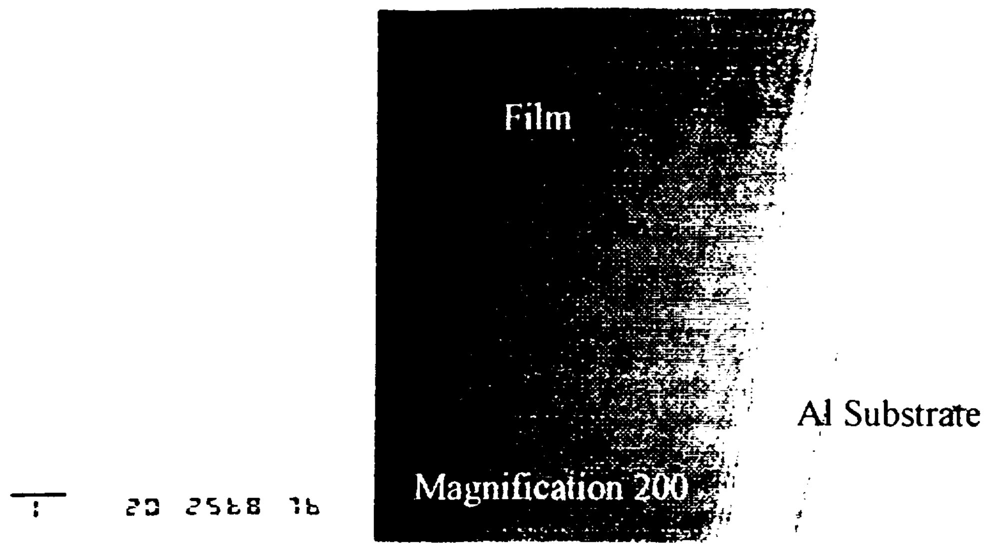
Table 1: Cleaning procedure:

STEP #	Chemicals	duration	remarks
1	boiling Tricloroethylene	1 min	degrease step
2	Acetone (room temp.)	1 min	none
3	boiling Methanol	1 min	none
4			repeat 2 times steps 1-3
5	DI water rinse	5 min	

The deposition of a thin few hundred Angstroms of Al on the Al foil prior to Si deposition was found to be beneficial to the avoidance of pin holes or adherence problems. Si and glass substrates were cleaned using conventional acid solutions. Si cleaning, in addition to the steps in Table 1 above, included 3 min. oxidation in HNO_3 followed by DI rinse and HF-based oxide removal. Glass substrate cleaning included 1 min. etch in HNO_3/HCl (1:1) followed by DI water rinse. GaAs substrates used in this work were epi-ready (no chemical surface preparation was required).

LUNAR REGOLITH THIN FILMS: VACUUM EVAPORATION AND PROPERTIES

Following optimization of various steps in the evaporation of Si, lunar-Si thin films were deposited using an e-beam evaporator. The Si extracted from the lunar regolith was loaded into the evaporation crucible. After conventional degreasing of all substrates, including crystalline Si (001), crystalline GaAs (001), Corning glass, and Al foil, they were loaded into the evaporation system facing the crucible. Substrates were partially masked by a 4-6 mm wide Al foil ribbon to allow for post growth thickness measurements. The chamber was pumped to a vacuum level of 10^{-7} torr. Prior to the evaporation substrates were outgased using IR heating setting the substrate temperature to 200°C for approximately 30 min. Then the electron beam was used to heat the regolith progressively, while a shutter prevented any evaporated material to be deposited on the substrates. The lunar-Si degas procedure was implemented for an approximate duration of 10 min. The electron beam power was increased to allow melting of the regolith. The pressure in the chamber increased to 3×10^{-6} Torr and then decreased to 1.3×10^{-6} Torr, which is typical for crucible degassing. The electron beam power was then adjusted to yield a deposition rate of 0.5 Angstrom/sec and the deposition process was initiated by opening the shutter and exposing substrates to the evaporation flux. The growth rate was monitored in-situ using a quartz microbalance, and approximately 2500 Å of lunar-Si thin film was deposited.



(a) (b)

FIGURE 3: (a) Plan View Scanning Electron Microscope Micrograph of Lunar-Si Evaporated on GaAs (001).

(b) Plan View Optical Microscope Micrograph of Lunar-Si Film Evaporated on 1 Mil (25 μm)-Thick Polycrystalline Aluminum Foil. Film (Left) is Essentially Following the Morphology of the Initial Foil (Right).

All films exhibited a specular morphology. Films deposited on polished Si, GaAs and glass substrates were extremely smooth and featureless under both high magnification optical microscope and scanning electron microscope (see FIGURE 1(a)). Films deposited on Al-foil essentially reproduced the morphology of the foil substrate (see FIGURE 1(b)). Thickness measurements were performed by a SLOAN DEKTAC profilometer and indicated nearly constant layer thickness of about 0.22 ± 0.02 μm for all samples, regardless of the substrate nature except for samples fabricated on Al foil where profilometry measurement was not possible due to the non planar nature of the surface. Relatively high uniformity ($\pm 10\%$) was obtained over the growth platform (about 30 cm in diameter).

Films Crystalline Structure

X-ray diffraction analysis were performed on all samples. Crystalline signatures were observed only from substartes for samples grown on Si or GaAs (monocrystalline) and Al foil (polycrystalline). The film diffraction pattern suggests that the deposited materials were highly nano-crystalline or amorphous in nature, which is consistent for Si-like materials deposited at relatively low substrate temperatures (< 300°C).

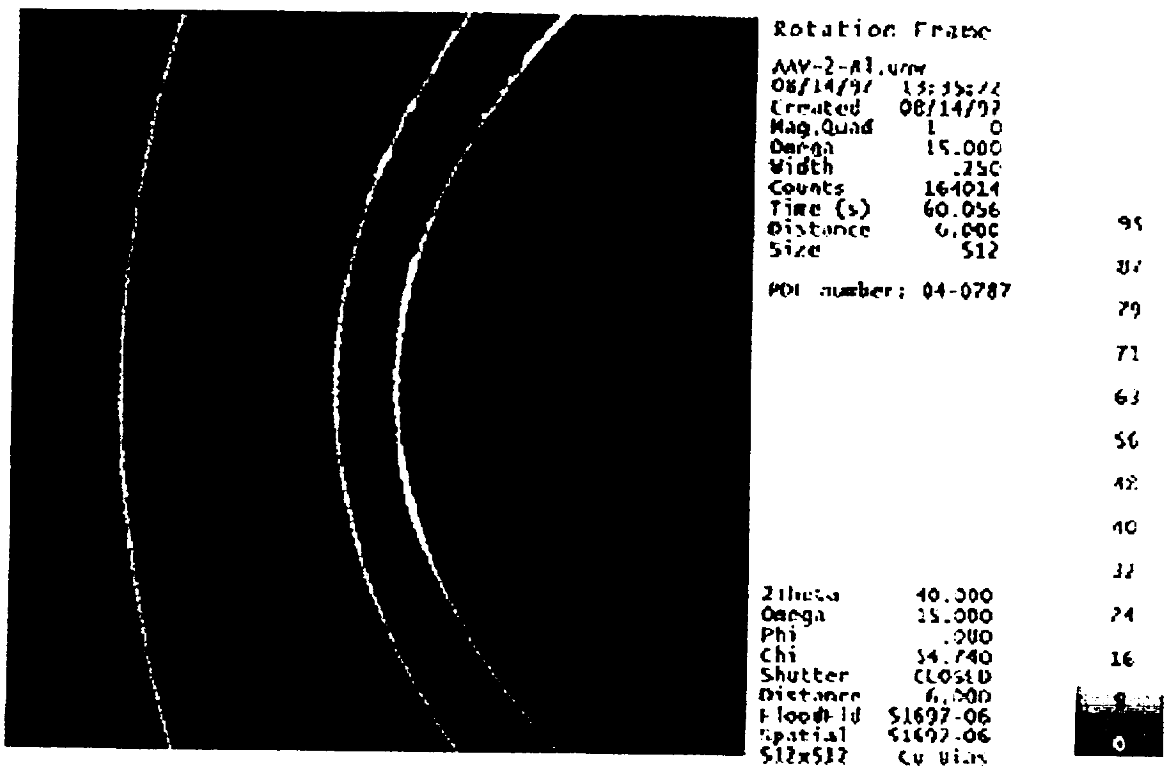


Figure 4: X-ray Diffraction (PHI scan) of Lunar-Si- Thin Film on 1 Mil - Aluminum Foil

Film Optical Properties: bandgap refractive index

Films deposited on glass substrates were found to be transparent with a slight red/brown coloration. In order to assess optical (refractive index) and electronic (bandgap) properties of the deposited films optical transmission spectra of the regolith on glass and a reference glass substrate were taken. Samples were placed between a 1 m-monochromator entrance slit and a Halogen white-light source chopped at about 1 kHz to reduce the effect of the ambient lighting. The transmitted light was detected using lock-in technique and a Peltier cooled InGaAs photodetector having cutoff wavelength of 1.8 μm (0.75eV). Figure 2 shows typical absorption spectra extracted from transmission analysis indicating the presence of a transparency bandgap occurring at about 1.1 eV. It is worth noting that the measured bandgap is consistent with that of pure crystalline Si, indicating that the films deposited using lunar regolith-extracted silicon have essentially the optical properties of crystalline silicon. Furthermore, taking into account the film thickness of e=0.22 μm and the period of undulations (λ=e/2n) observed in the absorption front, the film refractive index n is estimated to be about 3.5.

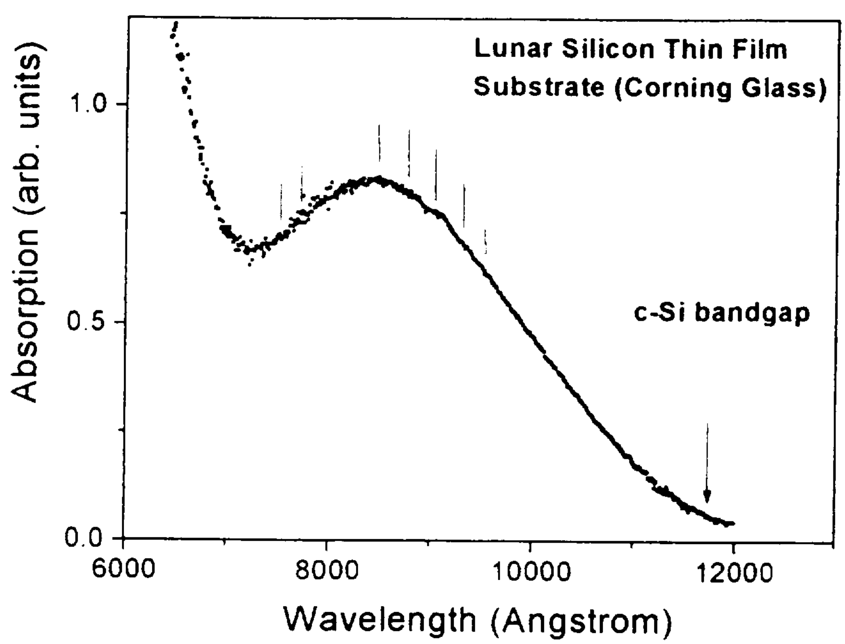


FIGURE 5. Optical Absorption of 0.22 μm Film Deposited on Glass. Undulation in the Absorption Front are Indicated. The Sample Transparency Gap Appears to be Very Close to That of a Single Crystal Si.

Si Thin Films Electrical Characteristics

Resistivity and Hall effect measurements were undertaken on several films fabricated on insulating (glass) or semi-insulating GaAs substrates. All as-grown films exhibit a p-type resistivity of about 50-100 Ω-cm. The p-type behavior is consistent taking into account the large amount of Al present in the startup lunar-Si (>200 PPM). However, these measurements were affected by the thickness of the films. According to Hall measurements the entire film area seems to be depleted of carriers (carrier concentrations below 10^{14} cm^{-3}), and therefore the resistivity and mobility measurements (6000-20000 $cm^2/Vsec$) are found to be seriously over-estimated. Small quantities of source materials available for this study did not allowed thicker films to be fabricated

Films Chemical Nature and Impurity Level

In order to assess the chemical composition of the deposited films Energy Dispersive Spectroscopy (EDS) and Secondary Ion Mass Spectroscopy analysis were undertaken. EDS analyses was performed using the EDS mode of a JEOL T300 scanning electron microscope. Besides the various substrate material chemical signatures, only silicon was detectable by EDS (see FIGURE 6) suggesting that films were mainly made of Si, as expected

To assess higher compositional sensitivity, secondary ion mass spectroscopy (SIMS) analysis was performed on samples fabricated on Al-foil. SIMS analysis of films deposited on glass were not possible due to the insulating characteristics of the substrates and charge accumulation effects. Quantitative analysis of Al in the films was not conclusive due to the nature of the substrate.

SIMS analysis confirmed the main element present in the films to be Si. The presence of Si-O complexes and hydrocarbon species were consistent with levels usually observed for silicon evaporated using ultra high purity (99.99999%) crystalline starting material and were most probably related to the exposure of the samples to ambient air.

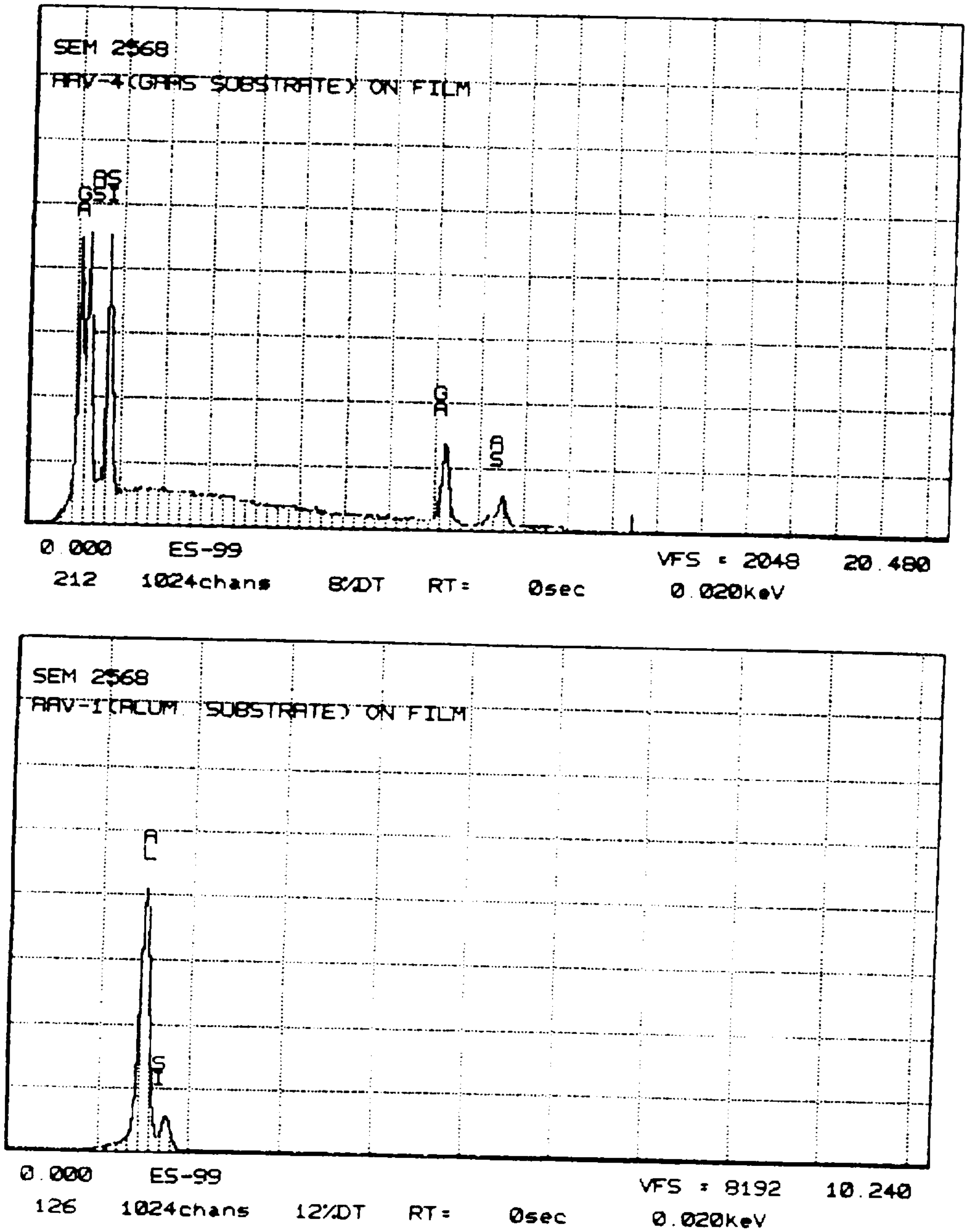


FIGURE 6. Energy Dispersive Spectra (EDS) of Lunar Silicon Thin Film on Al and GaAs Substrates.

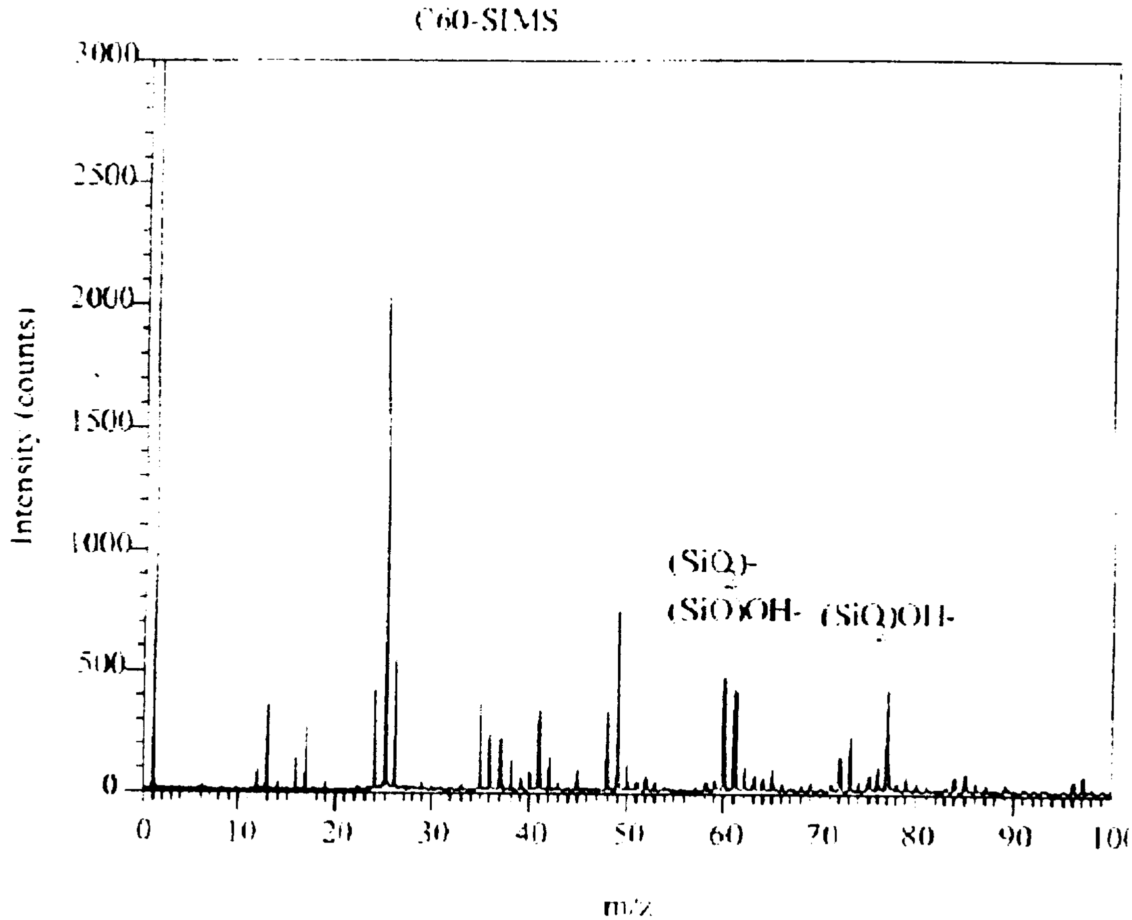


Figure 7: Surface SIMS from Lunar-Si Material: Presence of Si-O-H is related to the surface exposure to air

However, none of the initial impurities encountered in the starting regolith, like Li, Ca, Cu, or Fe were detectable by SIMS, setting their level to below 1 PPM (see Table 2). It seems that e-beam vacuum evaporation results in further purification of the processed regolith. Since Ca, Li, Cu and Fe vapor pressures at temperatures where Si is evaporated (1500-1600°C) are several orders of magnitude higher than that of Si and probably are evaporated completely during the Lunar-Si degas procedure and before Si evaporation. The degas procedure in our case lasted only about 10 min. It is worth noting that these impurities at the levels initially observed in the regolith (Table 2) may severely affect the performance of an electronic device. The apparent reduction or lack of the impurity content in the films is a positive sign which sets the quality of generated Si-films very close to that of micro-electronic quality standards.

Table 2 : Comparison Between Impurity Levels Measured in Starting Lunar-Si and Films Deposited on Al Foil.

Impurities	Impurity levels in Si extracted from lunar regolith	Impurity measured by SIMS on regolith films deposited on 1 mil-thick Al-foil
Aluminum (Al)	240 PPM	Non conclusive
Calcium (Ca)	175 PPM	< 1 PPM
Lithium (Li)	31 PPM	< 1 PPM
Copper (Cu)	20 PPM	< 1 PPM
Iron (Fe)	18 PPM	< 1 PPM

(*) As measured by R. Keller from EMC Consultants.

CONCLUSION AND FUTURE INVESTIGATIONS

In summary, a preliminary study of the vacuum evaporation of Si extracted from lunar regolith has been undertaken using a conventional electron gun evaporation technique. Thin films were evaporated on variety of crystalline substrates as well as on glass and lightweight 1 mil-thick Al-foils. Evaporated films have essentially semiconducting properties similar to those obtained from high purity silicon. Optical absorption analysis sets the bandgap of these films at about 1.1 eV; very close to that of crystalline silicon. Refractive index of the films is estimated to about 3.5. Secondary ion mass spectroscopy and energy dispersive spectroscopy analysis of these films indicates that they are essentially made of pure Si. While the purity of the films obtained with the "lunar waste material" is beyond the one of the "microelectronic-grade silicon" it seems that the vacuum evaporation of the lunar waste results in a further purification of the start up material and that the film obtained with this technique yields higher purity Si.

Our preliminary data on film purity and optical properties seem to be adequate for the fabrication of average performance thin film solar cells. Larger grain polycrystalline films should be attainable by heating the substrate during the evaporation.

Under a conservative scenario of 3-6% efficiency, it is projected that a 10 inch (25.6 cm) diameter solar cell will have a power output of ~2-4 W. Based on an e-beam vacuum growth of the silicon solar cell, the energy payback could be as short as 150 to 300 hr. This approximately 6 to 12 earth day payback period is quite short. This makes the solar cell lunar vacuum growth technique essentially 'self-generating' in that the grown cells could, after about two weeks, generate excess energy that would be used to grow more cells. It is true that n-type Si dopants such as As or P are not readily available on the moon. However, doping levels required to be in the 5-10 PPM range will require less than 50g dopant material for producing about 1 km^2 of solar cells (2-4 MW).

The proof-of-concept of lunar vacuum evaporation of waste silicon thin film on low cost and lightweight substrates such as Al-foil promises to be have a major impact on the lunar exploration initiative and power generation using resources available on the surface of the moon.

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